We thank the two reviewers for the detailed and helpful comments on our manuscript. We hope to have addressed all raised issues in our response and in the revised manuscript.

In their manuscript “Controls on fire activity over the Holocene,” Kloster et al. describe paleo-fire simulations made using global fire model driven by changes in climate and vegetation. They compare simulated area burned to inferences from paleofire records (from charcoal data), and assess the relative importance of different forcing variables on past burning among several large regions. Overall the analysis is well-conceived, the data appear to be of high quality, and the paper is nicely written and easy to follow. I would like to see a more thoughtful interpretation of the results and have a number of other minor suggestions, but otherwise recommend the manuscript for publication.

Major comment:

My main criticism of the paper is that it presents little interpretation of the re- sults. Presently there is no “Discussion” or similar section, and the only interpreta- tions/implications are given in a rather light “Conclusions” section. I think the paper would be most improved by adding a more in-depth discussion of its findings. I encour- age the authors to think critically about the aspects of their study that they find most compelling and focus on these, but also offer three suggestions that stand out to me here.

R1.1 - First, there is no discussion of the extent to which effects of different forcing variables on simulated burning depends on past variability in those variables versus sensitivity of the fire regime (real or simulated) to them. This distinction is very important–as an ex- treme example, note that either a constant Holocene climate or complete insensitivity of fire regime to climate would lead to the conclusion that climate variability was unim- portant to past fire regime change, but the implications are obviously quite different. At minimum this distinction needs to be assessed thoughtfully, and I would think that doing so would lead to fruitful ground for further discussion (e.g. implications for future change). Note also that the below suggestion (see “Minor comments”) to present the forcing data in a more interpretable form (i.e., not as unitless ratios) would probably be helpful here.

We extended the fire model description and present more in detail the sensitivity of the fire model to the single forcing variables in the Method section of the revised manuscript: ”Soil moisture, aboveground biomass, and wind speed control the burned area in the fire model. A high soil moisture lowers the fire occurrence probability and the overall fire spread. The model assumes that above a moisture of 0.35 a fire gets extinguished. A high aboveground biomass assures a high fire occurrence probability. The fire model scales the fire probability constrained by fuel availability linearly between a lower aboveground biomass amount of 200 gC/m^2 and an upper amount of 1000 gC/m^2. A high wind speed increases the fire spread and the burned area. An increase in wind speed from 15 to 20 km/hour, for example, results in an increase in the fire spread rate of 25% based on observations (Arora and Boer, 2005).“

In the Result section we included more detailed information on the strength of the single changes impacting burned area and extended the discussion in the Conclusion section (changes are highlighted in red in the revised manuscript).

R1.2 - Second, I find the discussion of charcoal- vs. simulation-based results (last paragraph in the paper) insufficient. Certainly it is true that discrepancies indicate that one or both data sources are “wrong”, but this is not a very insightful conclusion. I think the authors have a responsibility to make a more critical evaluation, at least of the simulated burned area, if not the charcoal data as well (which is perhaps not their expertise). As a particular example, simple “uncertainties” do not sufficiently explain the completely opposite trends of charcoal vs. simulation data in Europe, which the authors mention specifically. Another obvious point of discussion here is the distinction between error in simulated burning due to deficiencies in the fire model, the climate model, and the forcing data used to drive the latter. As experts in the fire modeling community, I believe the authors should be able to weigh in insightfully here. Overall, I agree with the statement (last line of the manuscript) that combining fire models and charcoal data could help reduce uncertainty in both. But this study is one of the first to take such an approach, so the authors need to be sure to set a good example of how such data-model insights can be gained.

We extended the discussion on charcoal versus simulation based results in the Result section (in the revised manuscript you can find these changes highlighted in red). However, we also stress that this discussion has been made already in detail in Bruecher et al., 2014, in which the same simulations were analysed and for example the opposite trends of charcoal vs. simulation data in Europe is

already discussed in greater detail. We added:

“Bruecher et al., 2014 compared in detail simulated burned area and charcoal data reported as z-scores. For the same regions as presented here Bruecher et al., 2014 found rank correlation between simulated burned area and charcoal data reported as z-scores between 0.32 and 0.66, with the highest correlation found for North America, which is also the region with the most charcoal data available (up to 83 charcoal sites).”

and

„Europe is the only analysed region for which the simulated burned area and the charcoal data show opposite trends. One reason for this discrepancy might be the missing anthropogenic fire control in our simulations. Molinari et al., 2013 showed in a modeling study that increased fire activity during the mid-late Holocene were primarily driven by changes in anthropogenic land cover, which we do not account for in our simulation.“

R1.3 - Finally, it is surprising that there is little discussion of implications to modern/future change. I think it is fine that the study focuses on pre-industrial changes, but clearly one of the key motivations for any paleo- analysis is to learn something relevant to the present Earth system state and potential future trajectory. Explicitly comparing simulated pre-industrial burning to modern (e.g. GFED database) seems entirely ap- propriate and within the scope of this paper, and could lead to some interesting insights about recent change (or at least about model performance, recognizing caveats about human activity, etc.). In any case, the relative importance of different forcing variables and the trajectory of past fire activity certainly have implications for future fire regimes in scenarios of global environmental change. The impact of the paper would be greatly improved if these were explored thoughtfully in the discussion.

We added a paragraph in the Conclusion section on the implications of our results for predicting future global fire activity (in the revised manuscript you can find these changes highlighted in red): ”Consequently, estimates on future fire activity can not only be based on e.g. temperature and precipitation trends derived from climate projections but require a more integrative approach. This could be based on process based fire models that are evaluated against observations including charcoal data or more complex causal functional relationships derived from observations that will greatly benefit from a further extension of the charcoal database. Future fire activity, however, will in many parts of the world be strongly anthropogenically disturbed, which limits the applicability of relationships derived from past fire activity to future climate conditions. Changes in land use, urban settlement, human ignition and fire suppression will all impact fire activity and will in many places of the world most likely dominate the overall change in fire activity (Andela and van der Werf, 2014, Kloster et al., 2012). Nevertheless, understanding the climate control on fire activity is essential for any future management plan that aims for a sustainable future.“

Minor comments:

R1.4 - P4260,L25–P4261,L6: The methodology is not entirely clear. E.g. what is the temporal resolution of CLIMBER-2 (I understand it’s not annual, but is it... 50-yr?); it sounds like the 50-yr base climate recycled over and over in sequence, but I’m not entirely sure; I don’t exactly understand how and why the “data presented here are smoothed...”. To be clear, I am not concerned that the methodology is flawed, it just isn’t explained clearly enough here. Finally, even if the method is mostly described by Brucher et al. 2014, some additional detail would be helpful, e.g. what variables are used to force the CLIMBER-2 model (solar, volcanic, and CO_2, as in the PMIP3 simulations?).

We extended our method sections, which hopefully makes the description now clearer:

“The simulations are setup similar to Bruecher et al., 2014. The base climate is represented by 50 years extracted from a MPI-ESM CMIP5 simulation, representative for the climate of the early industrial period (1850--1899). CLIMBER-2 simulated climate anomalies are added to this 50 year spanning annual varying base climate. The resulting climate is used as forcing for JSBACH. This approach is required as CLIMBER-2 does not simulate year-to-year climate variability, which is however critical to simulate land and vegetation dynamics in JSBACH. Unlike in Bruecher et al. 2014 we choose not a year randomly out of the 50 year base climate, but applied a constant base climate cycle, i.e. every 50 years cycle followed the same sequence. As a result the data presented here does not have any year-to-year variability when smoothed over 50 years or a multitude thereof.“

R1.5 - P4262,L6-8: Again, I do not understand what was done (seems related to comment above).

We extended the description of the factor experiments (see also comment R2.2): “This experiment serves as reference for the factor experiments. In the factor experiments one single forcing factor is varying over time. The others are prescribed continuously over the simulation period as a constant 50 year cycle, representative for 8K conditions (7999 to 7950 cal yr BP) and are taken from the output of the reference experiment FMW.“

R1.6 - P4262, L15-17: Fig. 1 shows only simulated data, so it is not suitable for illustrating whether the model does a good job to “capture major burning regions...” For this, a comparison to GFED or another observation-based fire map would be required. As noted above, I do think the authors should consider making such a comparison, even though there are caveats as they note.

Following the reviewers suggestion we included the burned area as reported in the GFED4 database into Figure 1 to facilitate comparison between our simulation and present day satellite based observed burned area.

P4263,L19-21: At least one point about wind speed bears further discussion: Is the lack of effect due to little change in simulated wind speed over the Holocene, or insen- sitivity of the fire model to wind speed? This is similar to the overall comment above about sensitivity vs. variability contributing to the importance of forcing variables, but exacerbated in this case by the fact that the wind data are not presented at all.

The model is actually sensitive to wind speed. We discuss this in more detail in the Method section in the revised manuscript: “A high wind speed increases the fire spread and the burned area. An increase in wind speed from 15 to 20 km/hour, for example, results in an increase in the fire spread rate of 25% based on observations (Arora and Boer, 2005).“ (see also comment R1.1). The simulated wind speed is however, not strongly changing over the Holocene for the analysed regions. We added this to the Result section: “All regions, have in common that changes in wind speed between 8000 and 200 cal yr BP do not significantly impact the fire activity, as the simulated wind speed changes over the Holocene are very small (less than 0.1% for the regions analysed). Therefore, the wind speed control on fire activity will not be further discussed for this study.“

R1.7 - P4263,L22-27: Based on Fig. 2a, the increase in the FMW experiment is <10%, but cited here as 11%–please double-check.

We corrected this. The numbers were taken from Table1, based on the non-smoothed data and therefore not directly comparable to Fig. 2.

R1.8 - P4265,L5-13: Can you confirm that the appearance of interactions is not due to repre- senting the simulated area burned as a % change relative to 8000 BP? If the different experiments have different absolute values of area burned, then the % change num- bers will not add up, even if no interactions are occurring. Regardless, an alternative standardization for the simulated data might be preferable, as it is a bit odd to compare the simulated data as ratios (% change) to differences (z-scores) in charcoal data in Fig. 2. (And in any case, the details/rationale for the standardization used need to be described in the Methods and/or figure caption–they are not currently).

All experiments start from the same control. As such the percentages (relative changes) do add up. We describe this now in more detail in the revised manuscript. "Results are presented relative to the 8K state (7900--7999), which is identical for all simulations." Z-scores are, however, no differences but normalized changes. This is also explicitly stated in the manuscript: "Z-scores are a standardized measure frequently used by the palaeofire community to compare aggregated values of past fire activity. They are, however, no quantitative measure and therefor cannot be related to absolute changes (Power et al., 2010)."

R1.9 - P4265,L18 and subsequent: Similar to the previous comment, the representation of the forcings as relative % change in Fig. 2 hampers comparison of the role of different forcing variables on simulated area burned across regions. E.g. Temperature is a key control in N. America, but appears to have a minor effect in Aust. Monsoon region, but it is difficult to judge this difference since both temperature series are represented as % change relative to an unknown absolute value. Again I would recommend showing the actual forcing data, or at least using a difference (vs. ratio) so that anomalies are given in familiar and comparable units.

We added a paragraph to clarify how the results are presented in this analysis and refer to Bruecher et al., 2014 for the absolute changes: "Results are presented relative to the 8K state (7900--7999), which is identical for all simulations. Absolute changes for burned area and a number of external forcing factors (precipitation, surface temperature, gross primary productivity, biomass carbon, soil carbon) are presented Figure 2 in the supplement of Bruecher et al., 2104." The reference to the absolute changes is now added to the caption of Figure 2.

R.1.10 Fig. 2: Yellow lines (charcoal data) not defined. Also, I believe citation should be Marlon et al. 2013, not 2009 (as in the text).

We corrected the reference and defined the yellow line in the revised manuscript (see also comment R2.9).

This short paper follows one from Brücher et al. (2014) where the same authors stud- ies how burned area and fire emissions have varied during the Holocene. The focus of this paper is to disentangle what drives the variations found in their earlier work fo- cusing on the effect of fuel availability, moisture, and wind speed. Given that climate variations over the Holocene were substantial enough to impact fires this is an inter- esting research area and after a substantial revision this paper would be a welcome addition to the literature.

My main critique is that after reading the paper I still have many questions about the findings and implications. This is partly due to the paper being so short. Splitting and expanding the Conclusions section into a longer discussion and shorter conclusion section would be helpful. Things that require additional discussion include:

R2.1 - How representative is the comparison between charcoal and models? In Australia for example the charcoal records are mostly in the SE while most fires burn in the N. For the comparison the authors could sample only those grid cells where charcoal records were derived from for example.

The representativeness between charcoal data and model has been assessed in the Bruecher et al., 2014. We pick up on this and state in the revised manuscript: "This comparison is done on a regional average even though the charcoal data are very site specific and some regions are only represented by a few charcoal sites, e.g. Sub-Saharan Africa has only 3 sites. The coarse resolution of the climate model, however, does not allow a site specific evaluation as the single site conditions (precipitation, temperature, etc.) can not be explicitly resolved, whereas region specific characteristics are in general expected to be captured.“

R2.2 - Conceptually, it is difficult (at least for me) to understand how fuel availability and moisture can be seen separately. Aren’t those tightly coupled? This is discussed in the Conclusions section but it would be better in the methods section.

In the revised manuscript we discuss the setup of the factor experiments, which allows us in the model to separate the fuel availability and fuel moisture control on fire activity, in more detail in the method section: “In experiment FMW all parameters controlling fire activity in the model are varying with time, i.e. the full set of forcing is applied and the simulated burned area represents fire activity over the Holocene. This experiment serves as reference for the factor experiments. In the factor experiments one single forcing factor is varying over time. The others are prescribed continuously over the simulation period as a constant 50 year cycle, representative for 8K conditions (7999 to 7950 cal yr BP), and are taken from the output of the reference experiment FMW.“

R2.3 - The modeled short-term variability is in general very low (gradual changes) while the charcoal record gives much more fluctuations. This requires discussion. Is it the smoothing? Are not all climatic changes represented in the model? Etc.

We extended the description in the Method section: “Unlike in Bruecher et al. 2013 we choose not a year randomly out of the 50 year base climate, but applied a constant base climate cycle, i.e. every 50 years cycle followed the same sequence. As a result the data presented here does not have any year-to-year variability when smoothed over 50 years or a multitude thereof.“ (see also comment R1.4).

R2.4- What are the implications of this study? The abstract ends with a statement that the findings are important to project future climate but there is very little about this in the main text. Including this would increase the impact of the paper. Clearly this requires also a balanced discussion between the role of climate and the role of humans.

We extended the discussion of future implications of our study (see also comment R1.3).

Minor comments:

R2.5 - P4260 L21: I assume it is 5 degrees instead of 51 degrees

51 is actually correct.

R2.6 - P4261 L12: "Fuel availability is simulated as a function of aboveground biomass". Since in many savanna ecosystems trees don’t burn (and higher tree densities of- ten lead to lower grass fuel loads which do burn) biomass is not the same as fuel availability. Please change or discuss in more detail.

We agree that aboveground biomass is only a crude proxy for the fuel availability. To discuss, however, the limitations of the fire model in detail is beyond the scope of our study. Here we refer the reader to the fire model publications (Arora and Boer, 2005, Kloster et al., 2010, Li et al., 2013), which discuss in detail the weaknesses of the fire model applied in the current study.

R2.7 - P4261 L15: "Human ignitions are not accounted for". I think this is fine for the purposes of this study given the limitations outlined by the author but it does limit the extrapolation to the future which should be discusses, see for example a recent paper by Andela et al (2014) in Nature CC showing that the human factor can already be seen in the satellite record in Africa.

We extended the discussion on the importance of our findings to assess future fire activity, including a discussion on the dominant role anthropogenic factors will play in the future (see also comment R1.3 and R2.4). We did also include the reference to the Andela and van der Werf (2014) study, which shows the dominant impact of landuse for Southern Africa already for present day conditions.

R2.8 - P4263, L10: "This trend fits to with an increase", please rewrite. Also some minor wording issues, for example inline -> in line (several occasions), therefor -> therefore

We corrected this in the revised manuscript.

R2.9 - Figure 2: These figures are too small to interpret easily. In addition a legend would be helpful for quick interpretation (right now the yellow line is not labelled, I assume this is the charcoal index, and in addition this color is difficult to see). It might be good to consider to make these separate figures

The figure will be enhanced in the revised manuscript. In addition, we changed the axis labeling to make the figure more readable and included a legend. The yellow line in now labeled and also details on the smoothing of the data are given in the revised manuscript (see also comment R1.10).

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Controls on fire activity over the Holocene

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Abstract

Changes in fire activity over the last 8000 years are simulated with a global fire model driven by changes in climate and vegetation cover. The changes were separated into those caused through variations in fuel availability, fuel moisture or wind speed which react differently to changes in climate. Disentangling these controlling factors helps to understand the overall climate control on fire activity over the Holocene.

Globally the burned area is simulated to increase by 2.5 % between 8000 and 200 cal yr BP with larger regional changes compensating on a global scale. Despite the absence of anthropogenic fire ignitions, the simulated trends in fire activity agree reasonably well with continental scale reconstructions from charcoal records, with the exception of Europe. For some regions the change in fire activity is predominantly controlled through changes in fuel availability (Australia-Monsoon, American Tropics/Subtropics). For other regions changes in fuel moisture are more important for the overall trend in fire activity (North America, Sub-Saharan Africa, Europe, Asia-Monsoon). In Sub-Saharan Africa, for example, changes in fuel moisture alone lead to an increase in fire activity between 8000 and 200 cal yr BP, while changes in fuel availability lead to a decrease. Overall, the fuel moisture control is dominating the simulated fire activity for Sub-Saharan Africa.

The simulations clearly demonstrate that both changes in fuel availability and changes in fuel moisture are important drivers for the fire activity over the Holocene. Fuel availability and fuel moisture do, however, have different climate controls. As such observed changes in fire activity can not be related to single climate parameters such as precipitation or temperature alone. Fire models, as applied in this study, in combination with observational records can help to understand the climate control on fire activity, which is essential to project future fire activity.

1 Introduction

Fires appeared on Earth soon after the onset of terrestrial plants and are an integral part of the Earth system (Bowman et al., 2009). Fires form an important natural disturbance process affecting vegetation distribution and structure (Scheiter and Higgins, 2009). Presently an area between 301 and 377 Mha burns annually (Giglio et al., 2013). Fires impact the climate through various processes, such as changes in surface properties and emissions of trace gases and aerosols into the atmosphere (Randerson et al., 2006; Ward et al., 2012; Keywood et al., 2013). At the same time fires are controlled by climate (Westerling, 2006; Harrison et al., 2010). Ongoing anthropogenic climate change is likely to alter fire activity (Scholze et al., 2006; Pechony and Shindell, 2010; Kloster et al., 2012). An analysis of paleorecords on fire activity can improve our understanding of the climate control on fire activity, which will be essential to project future fire activity and climate change.

Microscopic charcoal pieces in sediments have been related to fire history for different parts of the world going back in time for thousands of years (Patterson et al., 1987; Whitlock and Millspaugh, 1996; Scott, 2002). The Global Charcoal Database (Power et al., 2010) has collected over 400 radiocarbon-dated charcoal records covering the Late Quaternary. This database and associated updates have been used in various studies to improve our understanding of fire history (Power et al., 2007; Marlon et al., 2008, 2009).

The charcoal database provides information about changes in past fire activity. To relate those to changes in climate is often not straightforward. Fire activity is affected by changes in climate by directly altering lightning ignition sources (Price and Rind, 1994) and fuel moisture (Dwyer et al., 2000; Westerling et al., 2003) and indirectly through changes in fuel availability and vegetation distribution (Westerling et al., 2003; Martin Calvo et al., 2014). The importance of these controlling factors for fire activity varies across climate regimes. In dry regions fire activity is typically limited by fuel availability, but fuel moisture is sufficiently low to lead to successful fire ignitions. Under moist climate conditions fuel availability is sufficiently guaranteed but fuel moisture is often too high to allow for fires to spread (van der Werf et al., 2010). Consequently, climate change will impact fire activity differently in different climate zones and fire regimes.

Here, we investigate the climate control on fire activity over the Holocene by disentangling the controls via fuel availability, fuel moisture and wind speed within a fire model (Arora and Boer, 2005; Kloster et al., 2010) embedded in a global land vegetation model (JSBACH, Raddatz et al., 2007; Brovkin et al., 2009; Reick et al., 2013). We simulate fire activity for the period

8000 cal yr BP until 200 cal yr BP with the land vegetation model coupled to a climate model of intermediate complexity (CLIMBER-2, Petoukhov et al., 2000; Ganopolski and Rahmstorf, 2001). Fire activity has been observed to change over this period as a result of climate change (Carcaillet et al., 2002; Marlon et al., 2013). With the help of a global model we want to understand the reason for those changes.

2 Method

This study applies the coupled climate-carbon cycle model CLIMBA (Brücher et al., 2014). CLIMBA consists of the earth system model of intermediate complexity CLIMBER-2 (Petoukhov et al., 2000; Ganopolski and Rahmstorf, 2001) and JSBACH (Raddatz et al., 2007; Brovkin et al., 2009; Reick et al., 2013), which is the land surface and vegetation model of the MPI Earth System Model (MPI-ESM, Giorgetta et al., 2013). CLIMBER is applied with a resolution of 51° (longitude) by 10° (latitude) to simulate atmosphere and land processes, while JSBACH runs on a higher resolution (3.75° × 3.75°) including a daily cycle. JSBACH and CLIMBER-2 are coupled following Kleinen et al. (2010).

The simulations are setup similar to Brücher et al. (2014). The base climate is represented by 50 years extracted from a MPI-ESM CMIP5 simulation, representative for the climate of the early industrial period (1850–1899). CLIMBER-2 simulated climate anomalies are added to this 50 year spanning annual varying base climate. The resulting climate is used as forcing for JSBACH. This approach is required as CLIMBER-2 does not simulate year-to-year climate variability, which is however critical to simulate land and vegetation dynamics in JSBACH. Unlike in Brücher et al. (2014) we choose not a year randomly out of the 50 year base climate, but applied a constant base climate cycle, i.e. every 50 years cycle followed the same sequence. As a result the data presented here does not have any year-to-year variability when smoothed over 50 years or a multitide thereof.

The default JSBACH model was extended by a process based fire model (Arora and Boer, 2005; Kloster et al., 2010; Krause et al., 2014) with updates according to Li et al. (2012). The fire model calculates the total fire occurrence probability as the product of three probability functions representing the availability of biomass, fuel moisture and ignition potential. The fire then spreads as a function of wind speed and soil moisture. Fuel availability is simulated as a function of aboveground biomass. Soil moisture is used as a surrogate for fuel moisture. Lightning ignitions are prescribed from a satellite based climatology (Cecil et al., 2012) extended by a latitudinal dependency of the cloud to ground vs. intra cloud lighting fraction (Price and Rind, 1994). Human ignitions are not accounted for. With poorly constrained data on human fire interaction over the Holocene, we do not see any means to include those in the present study. However, fire models that do not explicitly account for human ignition can still reproduce the main features of the fire regime even in areas in which many fires are set by humans as has been shown by Prentice et al. (2011). Humans often set fire in regions that are fire prone, as such human ignitions tend to preempt, rather than augment, the natural fire regime (Prentice et al., 2011).

Soil moisture, aboveground biomass, and wind speed control the burned area in the fire model. A high soil moisture lowers the fire occurrence probability and the overall fire spread. The model assumes that above a moisture of 0.35 a fire gets extinguished. A high aboveground biomass assures a high fire occurrence probability. The fire model scales the fire probability constrained by fuel availability linearly between a lower aboveground biomass amount of 200 $\mathrm{gC/m^2}$ and an upper amount of 1000 $\mathrm{gC/m^2}$. A high wind speed increases the fire spread and the burned area. An increase in wind speed from 15 to 20 $\mathrm{km/hour}$, for example, results in an increase in the fire spread rate of 25% based on observations (Arora and Boer, 2005).

For this study we performed several experiments to disentangle the control of these single forcings on the simulated fire activity over the Holocene (Table 1).

In experiment FMW all parameters controlling fire activity in the model are varying with time, i.e. the full set of forcing is applied and the simulated burned area represents fire activity over the Holocene. This experiment serves as reference for the factor experiments. In the factor experiments one single forcing factor is varying over time. The others are prescribed continuously over the simulation period as a constant 50 year cycle, representative for 8K conditions (7999 to 7900 cal yr BP) and are taken from the output of the reference experiment FMW.

In experiment M only the soil moisture is varying with time; fuel availability and wind speed are kept constant over time. In experiment F only the fuel availability if varying with time; soil moisture and wind speed are kept constant. In experiment W only the wind speed is varying with time, soil moisture and fuel availability are kept constant.

3 Results

In 200 $\mathrm{cal\,yr\,BP}$ on average 528 Mha burn annually (see also Brücher et al., 2014), which is on the higher end of present day satellite based observed estimates (Giglio et al., 2013). The simulation presented does, however, not account for the human-fire impact and uses dynamically simulated natural vegetation cover not including agricultural areas. As such the simulations are not directly comparable to present-day satellite based observations. Overall, the model does capture the major burning regions in sub-Saharan Africa, Southeastern Asia, Northern Australia and parts of North and South America (Fig. 1a).

Globally the change in burned area is small over the Holocene with a slight increase in fire activity simulated between 8000 and 200 $\mathrm{cal\,yr\,BP}$ ($+14\,\mathrm{Mha}$ ($+2.5\,\%$)). Regionally, however, the simulation shows areas with pronounced increases (e.g. central Africa, parts of Australia and southern Europe) as well as decreases (e.g. in northern North America and in South America), which nearly compensate on a global scale (Fig. 1b). Brücher et al. (2014) has shown that the simulated climate over the Holocene is characterised for the northern tropics by an intensified and northward shifted monsoon system, which leads to a widespread greening between 8000 and 4000 $\mathrm{cal\,yr\,BP}$ in line with previous findings (Claussen, 1997; Brovkin et al., 2002; Prentice et al., 1992). Between 20–30° S drier conditions are simulated when zonally averaged during the time period 8000 to 6000 $\mathrm{cal\,yr\,BP}$. This is a result of drier conditions in South Africa (caused by the northward shifted monsoon system), drier conditions in Amazonia and a small increase in precipitation in Australia. These changes in climate alter fire activity over the Holocene as shown by Brücher et al. (2014). Here we disentangle further what caused these changes in fire activity.

Similar to Brücher et al. (2014) we analyse the transient evolution of the burned area between 8000 and 200 cal yr BP averaged over continental scale regions. Figure 2 and Table 2 depict the changes in burned area for the control simulation in which the fire submodel is driven with varying fuel availability, moisture and wind speed (experiment FMW), i.e. all parameters impacting fire activity are varying and the simulation is identical to the one presented in Brücher et al. (2014). The single factor experiments, in which only one parameter impacting fire activity is varying over time, are shown as well in Fig. 2 and are summarised in Table 2. The regions are chosen as analogs to Marlon et al. (2013) to facilitate comparison with changes in fire activity reported in the charcoal database. The fire activity is reported in z-scores in the charcoal database. Z-scores are a standardized measure frequently used by the palaeofire community to compare aggregated values of past fire activity. They are, however, no quantitative measure and thereforef cannot be related to absolute changes (Power et al., 2010).

Brücher et al. (2014) compared in detail simulated burned area and charcoal data reported as z-scores. For the same regions as presented here Brücher et al. (2014) found rank correlation between simulated burned area and charcoal data reported as z-scores between 0.32 and 0.66, with the highest correlation found for North America, which is also the region with the most charcoal data available (up to 83 charcoal sites). This comparison is done on a regional average even though the charcoal data are very site specific and some regions are only represented by a few charcoal sites, e.g. Sub-Saharan Africa has only 3 sites. The coarse resolution of the climate model, however, does not allow a site specific evaluation as the single site conditions (precipitation, temperature, etc.) can not be explicitly resolved, whereas region specific characteristics are in general expected to be captured.

In the following we will focus on the impact of fuel availability and moisture on fire activity over the Holocene for the single regions. Results are presented relative to the 8K state (7900–7999), which is identical for all simulations. Absolute changes for burned area and a number of external forcing factors (precipitation, surface temperature, gross primary productivity, biomass carbon, soil carbon) are presented Figure 2 in the supplement of Brücher et al. (2014).

All regions, have in common that changes in wind speed between 8000 and 200 cal yr BP do not significantly impact the fire activity, as the simulated wind speed changes over the Holocene are very small (less than 0.1% for the regions analysed). Therefore, the wind speed control on fire activity will not be further discussed for this study.

For the Asian Monsoon region (Fig. 2a) the simulated burned area increases between 8000 and 200 cal yr BP by around 9 %. For the same time period, the charcoal data reports an increase in fire activity as well. The increase in simulated burned area is primarily driven by reduced moisture in response to decreases in precipitation (15 %). For the Asian Monsoon region precipitation decreases by 17%, which equals ~150 mm/year. Changes in fuel availability alone have only a minor impact on fire activity for this region (1 %).

For North America (Fig. 2b) the burned area increases between 8000 and 200 cal yr BP (+4 %), which agrees with the increase reported in the charcoal database. Changes in fuel availability alone lead to a small increasing trend (+2 %), while changes in moisture dominate the overall increase in fire activity (+6 %). Noticeable is a lower fire activity between 7000 and 5000 cal yr BP, which is in accordance with a simulated drop in temperature within that period (~ −5%, which equals ~ 0.20 degrees C).

For Sub-Saharan Africa (Fig. 2c) the simulated burned area decreases between 8000 to 3000 cal yr BP (−2 %) and remains almost constant afterwards. In contrast, the charcoal data indicates lower fire activity during the time period 8000 to 2000 cal yr BP compared to the time period 2000 to 200 cal yr BP. The decrease in simulated burned area is dominated by the biomass control on fire activity, which leads to a decrease in burned area between 8000 and 200 cal yr BP (−5 %). This trend fits to with an increase in desert extent between 8000 and 200 cal yr BP by ~ 17% and a decrease in precipitation by 6%, which equals ~ 50 mm/year).

For the American Tropics (Fig. 2d) the burned area shows an increase between 8000 and 200 cal yr BP (+4 %). Similar findings are reported in the charcoal data, with somewhat lower levels between 4000 and 200 cal yr BP compared to the period 6000 to 4000 cal yr BP. Overall the trend in fire activity is dominated by a fuel availability control (+4 %), which red scales linearly with an increase in available biomass (+3%). Changes in fire activity due to moisture are smaller (+1 %) and in line with the simulated small decrease in precipitation (0.3%, which equals ~30 mm/year).

For Europe (Fig. 2e) the burned area decreases over the Holocene. In 200 cal yr BP the burned area is approximately 23 % lower compared to 8000 cal yr BP. For the same time period the charcoal data show an increase in fire activity. The simulated changes in burned area for Europe can be largely explained by the moisture control on fire activity, while changes in fuel availability alone result in a smaller decrease (−25 % compared to −10 %, respectively). Biomass decreases when averaged over Europe between 8000 and 200 cal yr BP (−3%), which is in line with the fuel availability driven trend in fire activity. Precipitation is increasing averaged over Europe in accordance with a decrease in fire activity driven by changes in moisture. Europe is the only analysed region for which the simulated burned area and the charcoal data show opposite trends. One reason for this discrepancy might be the missing anthropogenic fire control in our simulations. Molinari et al. (2013) showed in a modeling study that increased fire activity during the mid-late Holocene were primarily driven by changes in anthropogenic land cover, which we do not account for in our simulation.

For the Australia Monsoon region (Fig. 2f) the burned area increases between 8000 and 200 cal yr BP (+8 %). The charcoal data show a drop in fire activity between 8000 and 7000 cal yr BP, an increase up to 5000 cal yr BP and constant fire activity thereafter. For this region the overall trend in burned area is to a large extent explained by changes in fuel availability (+9 %), whereas changes in moisture have no impact on fire activity averaged over the region.

Moisture, fuel availability and wind speed do not control the fire activity independently but interact with each other. As such the system is non-linear, i.e. changes in burned area caused by changes in fuel availability, moisture and wind speed alone do not add to the changes in burned area which are simulated when fuel availability, moisture and wind speed are changed simultaneously. This is also reflected in the model simulations. For all regions we find negative synergies, i.e. the changes in burned area are smaller when driving factors are changed simultaneously (control simulation, experiment FMW) compared to adding the response of the individual experiments, in which only one forcing factor at a time is changed (adding the experiments F, M and W).

4 Conclusions

Globally the burned area is simulated to increase by 2.5 % between 8000 and 200 cal yr BP. Regionally, however, the change in burned area is larger with decreases and increases nearly compensating on a global scale.

While in some regions the burned area changes are predominantly controlled via changes in fuel availability (Australia-Monsoon, American Tropics/Subtropics) others are stronger impacted via changes in fuel moisture (North America, Europe, Asia-Monsoon, Sub-Saharan Africa). Fuel availability and fuel moisture do have, however, different climate controls. While for example precipitation generally allows the build up of fuel load it also increases fuel moisture; both processes having opposite effects on fire occurrence, i.e. an increase in precipitation leads in regions in which fuel availability is the dominant controling factor to an increase in burned area and decreases burned area in regions were fuel moisture is more important. In our analysis, we find for example that an increase in precipitation increases the burned area in Australia and decreases the burned area in Europe. As such, the present study clearly shows that the climate control on fire activity is difficult to assess from simple climate indices (such as temperature or precipitation) and paleo-fire records alone as done previously (e.g. Marlon et al., 2008, 2009). Only more complex relationships taking into account more than one explaining climate variable might be suitable to interpret the climate control of past fire activity (Daniau et al., 2012). Consequently, estimates on future fire activity can not only be based on e.g. temperature and precipitation trends derived from climate projections but require a more integrative approach. This could be based on process based fire models that are evaluated against observations including charcoal data or more complex causal functional relationships derived from observations that will greatly benefit from a further extension of the charcoal database. Future fire activity, however, will in many parts of the world be strongly anthropogenically disturbed, which limits the applicability of relationships derived from past fire activity to future climate conditions. Changes in land use, urban settlement, human ignition and fire suppression will all impact fire activity and will in many places of the world most likely dominate the overall change in fire activity (Andela and van der Werf, 2014; Kloster et al., 2012). Nevertheless, understanding the climate control on fire activity is essential for any future management plan that aims for a sustainable future.

Fire models can help to understand the climate control on past fire activity, as shown in this study. However, fire models are limited in their ability to reproduce global fire activity as they are build on a still incomplete process understanding on vegetation fire occurrence (Pfeiffer et al., 2013; Kloster et al., 2010; Pechony and Shindell, 2010). The human control on vegetation fires through fire ignition and fire suppression are controlled by population evolution and various social-economical factors (Archibald et al., 2012), which are difficult to assess on a global scale. In this study we are, therefore, not able to account for human ignition. Lightning ignition are kept constant even though they are climate controlled (Price and Rind, 1994), but no data on lightning occurrence over the Holocene is available.

The most striking mismatch between simulated fire activity and fire activity derived from charcoal data is found for Europe, showing opposite trends in the simulation and the observations over the Holocene. While this might be a result of the model itself caused by a missing anthropogenic fire control, it might be also caused by uncertainties in the charcoal data or an averaging over large regions that include different fire regimes with different climate controls. Combining fire models and charcoal data more closely in future studies could help to overcome the high uncertainties related with fire modeling as well as reconstructing fire activity from charcoal records.

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Table 1. Experiments performed for this study keeping single forcing factors controlling simulated fire activity constant or varying over the simulation period 8000 to 200 cal yr BP.

	fuel availability	fuel moisture	wind speed
F	varying	constant	constant
M	constant	varying	constant
W	constant	constant	varying
FMW	varying	varying	varying

Table 2. Difference in burned area between 200 and 8000 cal yr BP (100–199 minus 7900–7999) relative to the 8000 cal yr BP state in [%] for different regions and experiments (F: fuel availability varying, M: moisture varying; W: wind speed varying; FMW: fuel availability, moisture and wind speed varying = control simulation). Regions are chosen according to Marlon et al. (2013). Significant values (confidence level higher than 95 % determined with a student-t test) are printed in bold.

	F	M	W	FMW
North America	1.87	**6.06**	−0.1	**4.68**
Europe	**−10.05**	**−25.23**	−1.24	**−22.75**
Asian-Monsoon	0.97	**14.70**	0.23	**9.38**
American Tropics/Subtropics	**4.09**	1.00	−0.29	**4.17**
Sub-Saharan Africa	**−4.75**	**4.15**	−1.84	**−2.25**
Australia-Monsoon	**9.18**	0.09	1.28	**7.74**

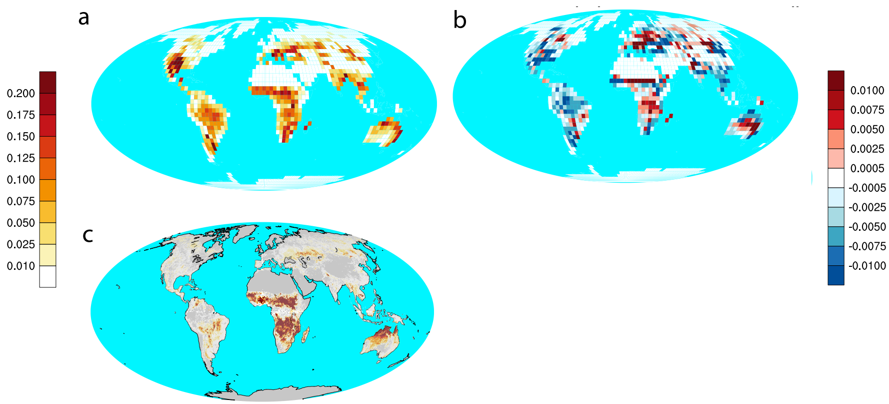

Figure 1. Simulated annual burned fraction of grid cell area [$m^2\,m^{-2}$] of natural fire activity for 8000 cal yr BP (a) and differences between 8000 and 200 cal yr BP (7900–7999 minus 100–199, b) Panel c shows the burned area based on present day satellite observations as reported in GFED4 (Giglio et al., 2013).

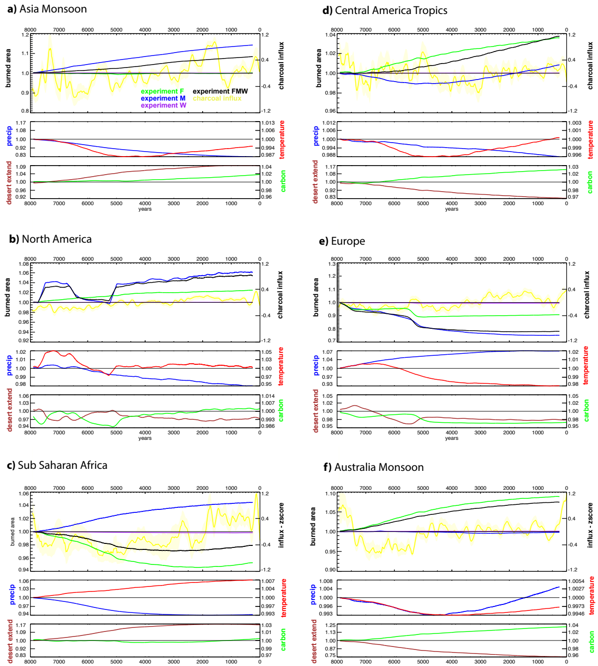
a) Asia Monsoon
b) North America
c) Sub Saharan Africa
d) Central America Tropics
e) Europe
f) Australia Monsoon
burned area
charcoal influx
influx - zscore
experiment F
experiment M
experiment W
experiment FMW
charcoal influx
precip
temperature
desert extend
carbon
years

Figure 2. Transient changes in burned area between 8000 and 200 cal yr BP averaged over continental scale regions (upper panels) for the experiments: FMW (black), M (blue), F (green), W (purple). The charcoal data is presented in yellow. The lower panels show changes in climate (precipitation (blue), surface temperature (red)) and vegetation state variables (land carbon storage (green), desert extent (brown)). The definition of the domains is taken from Marlon et al. (2013). Changes are normalized with respect to the 8000 cal yr BP state and smoothed with a 250 year running mean similar to Brücher et al. (2014); Marlon et al. (2013). Absolute changes for burned area and a number of external forcing factors (precipitation, surface temperature, gross primary productivity, biomass carbon, soil carbon) are presented Figure 2 in the supplement of Brücher et al. (2014).